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Heat transfer and fluid flow characteristics in microchannels heat exchanger using nanofluids: A review

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ABSTRACT

Advancement in the electronics industry led to the development of microscale heat transfer devices which offered high heat transfer coefficient in a compact size. Nevertheless, the heat transfer characteristics were limited by the heat transfer fluids that were used. The recent development of nanotechnology led to the concept of using suspended nanoparticles in heat transfer fluids to improve the heat transfer coefficient of the base fluids. The amount of research done in this particular field is fairly new and limited. Most studies done on microchannel devices and nanofluids recently have reported enhanced heat transfer capabilities and results that challenge traditional theories and limitations on heat transfer devices and fluids. Several important aspects of microchannel heat exchangers that affect the performance such as channel geometry, fluid inlet and outlet arrangement, type of construction were discussed together with the reported findings from experimental, numerical and theoretical literatures. This review also focuses on the important aspects of nanofluids such as types, properties and heat transfer characteristics and limitations towards the application of nanofluids. Apart from that, a comprehensive review on the work done regarding to heat transfer and fluid flow characteristics in microchannels heat exchanger using conventional fluids as well as nanofluids is also described.

Contents

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Nomenclature

CFD	computational fluid dynamics
c_p	heat capacity (J/(kg K))
D	characteristics diameter (μm)
E	effectiveness
h	heat transfer coefficient (W/(m^2 K))
HE	heat exchanger
k	thermal conductivity (W/(m K))
k_B	boltzmann constant, $k_B = 1.381 \times 10^{-23}$ J/K
k_f	fluid thermal conductivity (W/(m K))
Kn	Knudsen number
Pr	Prandtl number
Re	Reynolds number
NF	nanofluids
NTU	number of transfer units
Nu	Nusselt number

Greek symbol

ρ	density (kg/m^3)
μ	viscosity ((kg m)/s)
ϕ	volume fraction of nanoparticles
Ψ	particle sphericity

1. Introduction

Heat exchangers play an important part in the field of energy conservation, conversion and recovery. Several studies have focused on direct transfer type (recuperator) heat exchanger, where heat transfer between fluids occurs through a separating wall or into and out of a wall in a transient manner. There are two important phenomena happening in a heat exchanger: fluid flow in channels and heat transfer between fluids and channel walls. Thus, improvements to heat exchangers can be achieved by improving the processes occurring during those phenomena. Firstly, the rate of heat transfer depends on the surface area to volume ratio, which means the smaller channel dimensions provide the better heat transfer coefficient. Secondly, improving the properties of the heat transfer fluids (nanofluids) can yield higher heat transfer coefficient in a heat exchanger. The application of microchannels heat exchanger is vast; however the amount of literatures done on this device using nanofluids is somehow limited (at authors' best knowledge). Thus, this literature review is intended to focus on the studies done on microchannels device including heat exchanger and heat sinks and the use of nanofluids in these devices to obtain the best understanding of the topic.

1.1. The rise of mini and micro scale devices

With the advancement in miniaturization technology and pronounced need for higher efficient equipments, mini-scale and micro-scale devices are proving to be beneficial and advantageous. For constant surface temperature, the Nusselt number is constant in the fully developed region, and is given by the value of 3.657, as shown by Eq. (1):

$$Nu_D = \frac{hD}{k} = 3.657 \quad (1)$$

where D is the diameter, h is the heat transfer coefficient, and k is the fluid thermal conductivity. By replacing $Nu_D = 3.657$ into Eq. (1) and solving for h gives:

$$h = 3.657\frac{k}{D} \quad (2)$$

Looking at Eq. (2), it can be concluded that the smaller the diameter, the larger the heat transfer coefficient. Based on this, Tuckerman and Peace [1] suggested the concept of using microchannel heat sink for very large scale integrated (VLSI) circuits to obtain high performance cooling about two decades ago. Since then, numerous studies have shown high heat transfer rate obtained by the use of microchannels cooling devices. According to Kandlikar et al. [2], the trend towards miniaturization is mainly driven by:

(a) The need for heat transfer enhancement.
(b) Increased heat flux dissipation in microelectronic devices.
(c) Emergence of microscale devices that require cooling.

Currently, microchannel heat exchanger is used in industries such as microelectronics, aerospace, biomedical, robotics, telecommunications and automotive. These microscale devices, commonly known as MEMS (Micro Electromechanical Systems) are getting more advanced and complex as the micro fabrication technology is progressing well with the trend. However, there are two factors that limit the heat transfer coefficients in a micro heat exchanger: the reduction in the channel dimensions was accompanied by higher pressure drop, and the amount of heat transfer was limited by the heat transfer fluid used.

1.2. The use of nanofluids

Nanofluids refer to engineered fluids that contain suspended nanoparticles with average size below 100 nm in traditional heat transfer fluids such as water, oil and ethylene glycol. Nanofluids display much superior heat transfer characteristics compared to traditional heat transfer fluids [3]. The idea of using metallic particles to increase the thermal conductivity of fluids is not a new concept. By knowing the fact that metals in solid form have much higher thermal conductivity (refer to Table 1) than fluids, Maxwell (1873) who was the one originally proposed the idea of using metallic particles to increase the thermal properties of fluids.

This was followed by many trials by dispersing millimeter and micrometer sized particles in liquids. However, these large particles had several problems such as particle sedimentation, passage clogging, erosion and high pressure drop. The recent development of nanotechnology, however, opened up the opportunity to revisit Maxwell's idea by using nanometer (one billionth of a meter) sized particles. Many literatures done on nanofluids reveal unprecedented thermal transport characteristics and created a whole new idea of super heat transfer fluids of the future.

2. Microchannel heat exchanger (MCHE)

2.1. Types and manufacturing

Microstructure heat exchangers generally share the same principles as conventional macroscale heat exchangers. Some of the basic designs that are comparable to macroscale devices are cross-flow and counter-flow heat exchangers but with much smaller characteristics dimensions (in the micro scale). Kang et al. [4] manufactured and tested oriented silicon based cross-flow micro heat exchanger using wafers with hundreds of high aspect ratio channels which were bonded together by diffusion bonding with aluminum as medium layers. Their experimental testing using water as the working fluid showed that the flow field was always laminar and at flow rates greater than 4.5 L/min, the maximum pressure drop reached was 2.47 bar. They concluded that silicon has excellent properties in mechanics heat transfer, and anti-corrosion, thus the (1 1 0) silicon based micro heat exchanger suits for the operations at high temperature and corrosive environment.

Kanlayasiri and Paul [5] introduced a fabrication method to produce parallel-flow NiAl microchannel arrays, which included some novel method for material synthesis, NiAl machining, and NiAl bonding. The fabrication was done using microlamination procedure for producing high-aspect-ratio (28:1) NiAl microchannel arrays and reactive diffusion bonding was used to join the NiAl laminae.

Brandner et al. [6] presented micro heat exchangers in the form of both microchannel devices (with different hydraulic diameters) and microcolumn array devices (with different microcolumn layouts) and made comparisons. Mechanical micromachining processes can create surface roughness of the order of below 0.1% of the channel height with suitable materials. In most cases microchannel devices operate in a mass flux range in which the flow is laminar because surfaces of such smoothness create only negligible disturbance in flow profile. They compared two different layouts of microcolumn arrays with respect to heat transfer capabilities at a given mass flow. It was inferred that the staggered array of microcolumns maximized the heat transfer and minimized pressure drop across the device compared with aligned array.

In another paper, Brandner et al. [7] discussed the details on the properties and manufacturing methods of microchannel heat exchangers. These devices can integrate microstructures with different shape, size and numbers. As for the materials, variety of materials including copper, stainless steel, nickel-based alloys and other metals or alloys can be used. They also pointed out that with special designs of the microstructures, extremely high specific thermal power of up to 1000 W/cm^2 can be transferred.

Table 1
Thermal conductivities of various solids and liquids.

Material	Thermal conductivity (W/(m K))
Metallic solids	
Copper	401
Aluminum	237
Nonmetallic solids	
Silicon	148
Alumina (Al_2O_3)	40
Metallic liquids	
Sodium (644 K)	72.3
Nonmetallic liquids	
Water	0.613
Ethylene glycol (EG)	0.253
Engine oil (EO)	0.145

2.2. Microfluidics

Morini [8] reviewed the experimental results of single-phase convective heat transfer in microchannels. The fields of friction factor, laminar-to-turbulent transition of flow and Nusselt number in microchannels were reported. They showed that in many cases the experimental data of the friction factor and Nusselt number in microchannels disagree with conventional theory and inconsistent among each other. It was concluded that the transition from laminar to turbulent in micro flow devices is characterized by critical Reynolds numbers larger than the conventional value. The critical Reynolds numbers depend on the wall roughness in a different way compared to large channels; and the numbers decrease with the microchannel hydraulic diameter. In the laminar regime, some researchers reported that the Nusselt number increases with the Reynolds number with an exponent ranging from 0.3 to 1.96 while others reported that the Nusselt number decreases when the Reynolds number increases. Nevertheless, in the turbulent regime, the Dittus–Boelter correlation and the Gnielinski correlation have to be corrected for microchannel flows. The high relative roughness of the walls increases the convective heat transfer in microchanels and finally the variation of viscosity with the temperature affects the heat transfer. Morini [8] suggested that further systematic study is needed to generate sufficient knowledge of the transport mechanism responsible for the variation of the flow structure and heat transfer in microchannels. Some of the theories that have been used to explain the deviations are rarefaction and compressibility effects, viscous dissipation effects, electro-osmotic effects (EDL), property variation effects, channel surface conditions (relative roughness) and experimental uncertainties are listed hereunder.

Yener et al. [9] carried out a comprehensive review on single phase forced convection in microchannels. It was inferred that:

i. Convective heat transfer in microchannels is different from conventional sized channels, significantly higher and depends on Knudsen, Prandtl, Brinkman numbers and the aspect ratio.
ii. The convective heat transfer in liquid microchannels is in the continuum regime, thus Navier–Stokes equations are valid.
iii. The geometry of the microchannel plate, hydraulic diameter and aspect ratio of individual rectangular microchannels has significant influence on the single-phase convective heat transfer characteristics.
iv. Significant total thermal resistance reductions are not achieved in turbulent flow through microchannels mainly because of the significant higher pumping power requirements offset the slight increase in the overall thermal performance, thus revealing the importance of laminar flow in microchannels.
v. Nusselt number reductions are observed as the flow deviates from the continuum behavior or as Knudsen number takes higher values.
vi. For fully developed laminar forced convection in microchannels, Nu is proportional to Re$^{0.62}$, while for the fully developed turbulent heat transfer Nu is predicted by the Dittus–Boelter correlation by modifying only the empirical constant coefficient from 0.023 to 0.00805.
vii. The flow transition point and range are functions of the heating rate or the wall temperature conditions and large liquid temperature rise in the microchannels, which causes significant liquid thermophysical property variations and, hence significant increase in the relevant flow parameters such as Reynolds number would occur. The transition point and range are affected by the liquid temperature, velocity, and geometric parameters of the microchannels.
viii. Prandtl number is important, since it directly influences the magnitude of the temperature jump. As Pr number increases,

the difference between the wall and fluid temperature at the wall decreases, resulting in greater Nu number values.

ix. Viscous heating is an important factor in microchannels since the ratio of surface area to volume is large, and especially important for laminar flow, where considerable gradient exists.

Bayraktar and Pidugu [10] reviewed the characteristics of liquid flows in micro fluidic systems. It was concluded that most experimental results on pressure drop and friction factor measurements reported in the literature are inconsistent and contradictory. They outlined that previous work on micro scale flow indicated early transition from laminar to turbulent flow and deviations between the predictions of conventional theory and experimental results on pressure drop and friction factor. It was inferred from the review that these reasons could be factors for the inconsistencies: experimental uncertainties in the measurements of channel dimensions and flow rates, difference in surface roughness, unaccounted Joule heating and viscous dissipation effects, unaccounted electro-viscous effects for pressure driven flows, unaccounted entrance and exit effects. It was suggested that studies which can measure the factors mentioned above are needed to completely understand the micro fluidics phenomena.

2.3. Experimental studies on MCHE

The effect of nanofluids was tested in mini heat exchanger by Mapa and Mazhar [11]. Their experiments tested the heat transfer performance in the heat exchanger using water/water as working fluids, and using water and nanofluid with concentration of 0.01% and 0.02% volume. They concluded that nanofluids enhance the heat transfer rate, and stated that the presence of nano particles reduced the thermal boundary layer thickness.

A micro-cross flow heat exchanger was analyzed using water by Kang and Tseng [12]. A theoretical model was developed and validated by comparing the theoretical solutions with the experimental data from the relative literature. The analytical results show that the heat transfer rate and pressure drop are strongly dependent on the average temperature of the hot and the cold side flow. For the case of same effectiveness, higher average temperature has larger heat transfer rate, while for the case of different effectiveness, the heat transfer rate and pressure drop decrease with the increase in effectiveness. Among the types of material tested in their analysis (silicon and copper), it was found that the influence of material is very low in microchannels due to the small thickness of the fins.

Lu and Nnanna [13] performed an experimental study of fluid flow in microchannel which has a trapezoidal manifold based on work done by Senta and Nnanna [14]. Their analysis further showed that flow uniformity among the channels largely depends on the shape of the manifolds, length and location of inlet and outlets, and the inlet flow rate. The experimental data also showed that microchannel has significant impact on the heat transfer rate for all flow rates. This was attributed to laminar flow in the channels, conduction heat transfer through the walls of the channels, fluid-channel wall interaction and microconvection within the channels.

Luoa et al. [15] conducted an experimental investigation of constructual distributor for flow equidistribution in a mini cross flow heat exchanger (MCHE). Their study included analysis of thermal performance and pressure drop with different assembly configurations of constructual distributors, conventional pyramid distributors and a mini cross flow heat exchanger. Their results suggest that the use of distributors can enhance thermal performance due to homogenized fluid flow, but at the cost of higher pressure drops. Among the configurations tested, conventional pyramid distributor and outlet with constructual collector showed higher thermal performance and lower pressure drop.

García-Hernando et al. [16] carried out an experimental investigation of fluid flow and heat transfer in a single-phase liquid flow micro-heat exchanger using deionized water. It was reported that no special effects related to the small dimensions such as heat transfer enhancement or pressure drop were observed during the experiment. The study was focused on the analysis of the hydrodynamic and thermal performance of two micro-heat exchangers, characterized by microchannels of $100\,\mu m \times 100\,\mu m$ and $200\,\mu m \times 200\,\mu m$ square cross-sections. The entrance region phenomena defining the heat transfer for medium and large Reynolds number was well predicted by existing correlations. For very low Reynolds numbers, the results did not completely agree with available models and correlations, which overestimate the convection coefficients. It was also reported that the plate thickness and material are critical in the design of micro heat exchangers as the plate conduction thermal resistance plays a major role in the performance characterization.

Another study on microchannels heat exchanger design was done by Park [17]. A liquid microchannels heat exchanger was designed and investigated with different channel width to find the maximum cooling efficiency when combined with pumping performance. The experimental results were compared with a recently developed correlation of heat transfer rate in terms of Nusselt number and Brinkman number by another research [18]. Conventional heat transfer theories and numerical commercial codes were also used to predict the cooling efficiency. The thermal resistance results were compared with numerical and conventional theories. It was found that the prediction from the new correlations agreed well with the measured minimum thermal resistance of the micro heat exchanger compared with conventional heat transfer theories and numerical commercial codes.

Pantzali et al. [19] performed a study on plate heat exchangers (PHE) using nanofluids as the working fluids. Their methodology included preparation of the nanofluids, measurement of the thermophysical properties of the nanofluids, experimental analysis and also CFD simulation to gain an insight of the flow inside the PHE. The results from the measurement of the thermophysical properties of the nanofluids yielded these findings: increase of thermal conductivity; increase of density; decrease of heat capacity; increase in viscosity; and possible non-Newtonian behavior. The experimental data showed that the thermo physical properties and type of flow inside the heat exchanger played important roles in the efficiency of the nanofluid as a coolant. It was concluded that in industrial heat exchangers where large volumes of nanofluids are required and the flow is turbulent, the use of nanofluids seems impractical.

Farajollahi et al. [20] performed an experimental analysis to study heat transfer of nanofluids in a shell and tube heat exchanger. The nanofluids used were Al_2O_3/water and TiO_2/water under turbulent flow conditions to investigate the effects of Peclet number, volume concentration of suspended particles, and particle type on the heat transfer characteristics. The results indicate that addition of nano particles to the base fluid enhances the heat transfer performance and results in larger heat transfer coefficient than that of the base fluid at the same Peclet number. It was noticed that heat transfer characteristics of nanofluids increase significantly with Peclet number. TiO_2/water and Al_2O_3/water nanofluids possess better heat transfer behavior at the lower and higher volume concentrations respectively. The experimental results were also in agreement with the predicted values of available correlation at the lower nanoparticle volume concentrations.

2.4. Numerical studies on MCHE

Raja et al. [21] performed a numerical simulation on heat transfer and fluid flow for constructual heat exchanger using water and air as operating fluids. The constructual heat exchanger featured

had multiple scales for the flow structure. The elemental channels of hot fluid were placed in cross flow with the elemental channels of cold fluid. The main objective of their work was to analyze the thermally developing fluid flow and heat transfer in the first construct and to make a comparative study with the fully developed ideal cross flow heat exchanger. The results show that the effectiveness for the flow rates considered was 10% greater than that of ideal cross flow heat exchanger. The higher heat transfer coefficients were attributed to small channel spacing and developing laminar flow.

In another numerical study done by Foli et al. [22], two approaches were used for determining the optimal geometrical parameters of the microchannels in micro heat exchangers. The first method was combined CFD analysis with an analytical method of calculating the optimal geometrical parameters of micro heat exchangers. The second method used was multi-objective genetic algorithms in combination with CFD. It was concluded that the performance of micro heat exchangers depends on the operating conditions and aspect ratio of the microchannels that make up the flow passages. The optimal geometry obtained from the first method leads to higher heat flux and heat transfer rates than conventional geometry heat exchangers. However, the second method's geometries were able to obtain even higher heat fluxes than those obtained using the first method.

Pääkkönen et al. [23] performed a numerical evaluation of heat transfer boundary conditions for CFD modeling of 3D plate heat exchanger geometry. This numerical study involved modeling of heat transfer and fluid flow and heat transfer in a corrugated geometry using Fluent software. The CFD models were verified with correlations and experimental data obtained by a flat plate test rig of which parameters were calculated analytically. The results show that the built in model in CFD has many deficiencies and problems due to the fact that many assumptions had to be made when defining the boundary conditions in the complex geometry. The convection boundary condition seems to describe most reliably the heat transfer in the corrugated geometry. For the flat plate geometry, the heat flux boundary condition was considered to be most suitable. These appropriate boundary conditions were found to agree with the results from the experiments and correlations in the literature.

Hasan et al. [24] studied the influence of channel geometry on the performance of a counter flow microchannel heat exchanger. Numerical simulation was done to solve 3D developing flow and 3D conjugate heat transfer to evaluate the effect of size and shape of channels on the performance. The effect of shape was studied using shapes such as circular, square, rectangular, iso-triangular and trapezoidal. It was observed that: decreasing the volume of each channel or increasing number of channels results in increased heat transfer and increase in required pumping power and pressure drop; circular shape gives the best overall performance in terms of thermal and hydrodynamic characteristics. Their study was also developed correlations for predicting effectiveness as well the performance index and was proven valid over a wide range of operating parameters.

Chein and Chen [25] studied numerically the inlet/outlet arrangement effect on microchannel heat sink performance. Finite

Table 2
The main findings from the experimental and numerical work related to MCHE.

Author	Type[a]	Method	Findings
Mapa and Mazhar [11]	E	Effect of NF on mini HE	NF enhance heat transfer rate Nanoparticles reduce thermal boundary layer thickness
Kang and Tseng [12]	T + E	Micro cross flow HE theoretically analyzed and compared with experimental data from relative literature	Heat transfer rate and average temperature strongly dependent on average temperature of fluid Influence of material type is minimal on MCHE
Lu and Nnanna [13]	E	Microchannel with trapezoidal manifold	Flow uniformity in channels depends on conditions at the inlet Microchannel has significant increase in heat transfer rate for all flow rates
Luoa et al. [15]	E	Effect of flow distributors in mini cross flow HE	Distributions enhance thermal performance and increase pressure drop
Garcia-Hernando et al. [16]	E	Single phase liquid flow in micro HE	No special effects related to small dimensions observed Plate thickness and materials are critical in design of micro HE
Park [17]	E	MCHE with different channel width, compare with new correlation of heat transfer in terms of Nusselt and Brinkman numbers	The new correlation has better accuracy prediction compared to conventional theories and commercial numerical codes
Pantzali et al. [19]	E + N	Plate HE with NF	Nanoparticles increase thermal properties NF not practical for industrial use
Farajollahi et al. [20]	E	Shell and tube HE with NF	Nanoparticles enhance heat transfer performance
Raja et al. [21]	N	Constructual HE using water and air	10% greater effectiveness than ideal cross flow HE due to small channel spacing and laminar flow
Foli et al. [22]	N	CFD and multi-objective genetic algorithm to determine optimum geometric parameters of the microchannel in micro HE	Multi-objective genetic algorithm method able to produce geometries with higher heat fluxes
Pääkkönen et al. [23]	N	Heat transfer boundary condition for 3D plate HE geometry	For corrugated geometry, the convection *boundary* condition is most reliable in determining heat transfer rate For flat plate geometry, the heat flux boundary condition is most suitable
Hasan et al. [24]	N	Influence of channel geometry of counter flow microchannel HE	Circular channel has best overall performance
Chein and Chen [25]	N	Inlet/outlet arrangement effect on microchannel heat sink performance	V-type arrangement had best performance Horizontal fluid supply has more velocity maldistribution
Al-Nimr et al. [26]	N	Fully developed thermal behaviors for parallel flow microchannel HE	*Kn* increase causes velocity slip and temperature jump across the wall increase as well NTU increase causes increase in effectiveness in HE

[a] E—experimental analysis, N—numerical analysis, and T—theoretical analysis.

volume method was used to solve the three-dimensional governing equations for both fluid flow and heat transfer. Under a given pressure drop across the heat sink, the resultant flow fields and temperature distributions are different according to the inlet/outlet arrangement. Using the thermal resistance, overall heat transfer coefficient and pressure drop coefficient to evaluate the heat sink performance, they concluded that the V-type heat sink had the best performance. Generally, heat sinks with horizontal fluid had more velocity maldistribution and this resulted in more serious temperature non-uniformity.

Al-Nimr et al. [26] studied numerically the fully developed thermal behaviors for parallel flow microchannel heat exchanger. The hydrodynamics and thermal behaviors of the flow in micro-heat exchanger parallel-plate are investigated by using continuum approach and slip condition at the boundary. The parameters considered in their study were Knudsen number (*Kn*), heat capacity ratio (Cr), the effectiveness (*e*) and number of transfer units (NTU). The results show that the increase of *Kn* number causes velocity slip and the temperature jump across the wall to increase as well. The increase in NTU increases the effectiveness in the heat exchanger while the increase in Cr led to reduction in effectiveness and *Kn* number. Some of the major findings related to MCHE studies reviewed previously are summarized in Table 2.

3. Nanofluids

3.1. Preparation

Nanofluids are produced by either one-step or two-step production methods [3]. The two important elements here are the nanoparticle material types and host liquid types. Nanoparticles used in nanofluids have been made of various materials, such as oxide ceramics (Al_2O_3, CuO), nitride ceramics (AlN, SiN), carbide ceramics (SiC, TiC), metals (Cu, Ag, Au), semiconductors (TiO_2, SiC), carbon nanotubes, and composite materials. The common host liquids are water, ethylene glycol, and oil.

3.1.1. Single-step process

This process involves condensing nanophase powders from the vapor phase directly into a flowing low-vapor-pressure liquid (nanoparticles are made and dispersed in liquid simultaneously). The nanoparticles are prepared by either using physical vapor deposition (PVD) technique or liquid chemical method [27]. One particular PVD method, known as VEROS (vacuum evaporation onto a running oil substrate) was initially invented to produce nanoparticles. However, this method did not receive any limelight due to the fact that it was difficult to separate the nanoparticles from the liquid. Based on this technique which was modified slightly, Eastman et al. [28] developed a direct evaporation system where Cu vapor is directly condensed into nanoparticles by contact with a flowing low-vapor-pressure liquid ethylene glycol. This process does not involve drying, storage, transportation, and dispersion of nanoparticles, thus during mixing agglomeration is minimized and fluid stability is higher. The thermal conductivity of ethylene glycol was increased by 40% at a Cu nanoparticle concentration of only 0.3%. However, the disadvantage of this process is that only low vapor pressure fluids can be used.

The second method is chemical synthesis. The one step method produced stable Cu-in-ethylene glycol nanofluids by reducing copper sulfate pentahydrate ($CuSO_4{\cdot}5H_2O$) with sodium hypophosphite ($NaH_2PO_2{\cdot}H_2O$) in ethylene glycol under microwave irradiation. The chemical method is faster and cheaper than the one step physical method described above. Recently, Wei et al. [29] developed a chemical solution method (CSM) to synthesize Cu_2O nanofluids by suspensions of cuprous-oxide (Cu_2O) in water. Their experimental studies showed a substantial thermal conductivity enhancement of up to 24% with their synthesized nanofluids. They also reported that the nanoparticle shape can be varied from a spherical shape to octahedral by adjusting some synthesis parameters.

3.1.2. Two-step process

In the two-step process [28], nanoparticles are produced first and then mixed with base fluids. This method is more extensively used to produce nanofluids because nanopowders are commercially available nowadays. Nanoparticles can be produced using either physical or chemical process. Examples of physical process include inert-gas condensation (IGC) and mechanical grinding. Examples of chemical fabrication methods include chemical vapor deposition (CVD), chemical precipitation, micro emulsions, thermal spray, and spray pyrolysis. Ball milling method can be used to produce alloyed nanoparticles of $Al_{70}Cu_{30}$. These nanoparticles are generally produced in powder forms and dispersed in aqueous and organic host liquids to produce nanofluids.

Since in two step process the preparation of nanoparticles is separated from the process of making nanofluids, agglomeration can occur during both stages, especially during drying, storage and nanoparticle transportation stage. This is primarily due to strong Van der Waals attractive force and most nanoparticles are in the form of dried agglomerates with much larger dimensions than the individual particles. Most nanofluids made using oxide nanoparticles and carbon nanotubes are made using this two step process while metallic nanoparticles are not suitable for this process. Ultrasonic equipment is commonly used to intensively disperse the particles and minimize agglomeration. Al_2O_3 nanofluid was produced using this method by Eastman at al. [28] and Lee at al. [30]. Hong [31] produced Fe nanofluids by mixing Fe nanocrystalline powder in ethylene glycol. To avoid nanoparticle aggregation, surfactants and ultrasonic agitation technique were used. Xie et al. [32] prepared Al_2O_3/H_2O, Al_2O_3/EG, AL_2O_3/PO nanofluids using two step process, and applied intensive ultrasonification and magnetic force agitation to avoid nanoparticle aggregation. This two step nanofluid synthesis technique is cheaper because nanopowder synthesis techniques are already scaled up to industrial production levels. Nevertheless, the issue of stabilization of the nanoparticle suspensions in the base liquid is still a concern.

3.2. Stability

Stability of nanofluids can be determined using many methods such as sedimentation method where the variation of concentration with sediment time is obtained with a special apparatus. Sedimentation photograph method where photos of nanofluids in test tubes is taken by a camera, and next is zeta potential analysis method. Zeta potential method has limitations whereby only the value of viscosity and concentration can be obtained. Peng and Yu [33] studied the factors that influenced the stability of nanofluids. They reported that the most important factors in determining the stability of the nanoparticle suspensions were its concentration, dispersant, viscosity of base fluid and finally the PH value. The diameter, density and the duration of ultrasonic vibration had also an effect on the stability of the suspensions. In a different study, Wang et al. [34] concluded that the equivalent diameter of nanoparticle and dynamic viscosity on nanofluids were most important in affecting the stability of the fluid. Nanofluids produced without stabilizers would change rapidly with time.

To overcome this problem, several methods such as the addition of surface active agents and control of liquid PH were used. Xuan and Li [35] used salt and oleic acid as stabilizers to increase the stability of Cu/oil and Cu/water nanofluids. Murshed et al. [36] used oleic acid and cetyltrimethylammonium bromide (CTAB) surface

active agents. Wei et al. [29] used some polyvinyl pyrrolidone (PVP) as surfactant in their $CuSO_4$ solution and observed stable nanofluids after 24 h. However, it should be noted that these methods change the heat transfer and flow behavior of the nanofluids. Besides that, these methods are only able to keep the particles stable for days or weeks at some instance. It is fair to mention that proper method to produce stable nanofluid is still not achieved and further research and standardized methods need to be established in order to obtain a systematic conclusion regarding this matter.

3.3. Heat transfer properties and characteristics

Wen et al. [37] stated that compared to conventional solid-liquid suspensions for heat transfer intensifications, properly engineered nanofluids possess the following advantages: (i) high specific surface area and therefore more heat transfer surface between particles and fluids; (ii) high dispersion stability with predominant Brownian motion of particles; (iii) reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification; (iv) reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization; and (v) adjustable properties, including thermal conductivity and surface wettability, by varying particle concentrations to suit different applications. The effectiveness of heat transfer is given by the heat transfer coefficient (HTC), h. This value depends on a number of thermo-physical properties of the heat transfer fluids such as thermal conductivity, k, heat capacity, c_p, viscosity, μ, density, ρ, and surface tension, σ, if phase change is involved. The general trend is HTC increases when effective thermal conductivity, specific heat and density increase, while HTC decreases with viscosity.

3.4. Mechanism of heat conduction

Since Choi et al. [38] reported that the addition of a small amount (less than 1% volume) of nanoparticles to traditional heat transfer liquid approximately doubled the thermal conductivity of the fluid, the frenzy into nanofluids research for heat transfer applications is started. Several other researchers have reported similar trend in the increase of heat transfer in conventional fluids by the addition of nanoparticles. For example, Masuda et al. [39] and Xuan and Li [40] stated that with low nanoparticle concentrations (1–5% by volume), the thermal conductivity of the suspensions can increase by more than 20%. Eastman et al. [28] reported that their experiments with suspended nanoparticles (5% volume CuO nanoparticles in water), the thermal conductivity is increased by approximately 60%.

The conventional understanding of the effective thermal conductivity of mixtures and composites is based on continuum formulations which typically involve only the particle size, shape and volume fraction as variables and assume diffusive heat transfer in both liquid and solid phases. The effects of solid/liquid interfaces or particle mobility are not taken into account. This method can provide a good description of systems with macrometer and micrometer sized particles, but fails to describe the unusual increase of thermal conductivity in nanofluids.

In an interesting theoretical analysis to find possible explanations of the anomalous increase of thermal conductivity of nanofluids, Keblinski et al. [41] analyzed a comprehensive list of factors that might explain the phenomena which macroscopic theory of heat transport in composite materials failed to explain. Those factors are: (i) the possibility that the enhancement of thermal conductivity arises from the Brownian motion of the nanoparticles; (ii) how much of an increase in the thermal conductivity can be expected from molecular-level layering of the liquid at the liquid/particle interface; (iii) the nature of heat transport in nanoparticles and the validity of the key assumption of the macroscopic theory of diffusive propagation of heat in both particles and in the liquid matrix; (iv) the effects of clustering of nanoparticles, both by forming direct solid–solid paths and by possible clustering effects mediated by liquid existing within the limit of a short interparticle distance. The findings made by their study are explained next.

3.4.1. Brownian motion

Brownian motion (particles moving through the liquid and colliding) is accounted for direct solid–solid transport of heat from one to another and ultimately increase thermal conductivity. Brownian motion is defined by the particle diffusion constant D, which is given by the Stokes–Einstein formula:

$$D = \frac{k_B T}{3\pi\eta d} \tag{3}$$

where k_B is Boltzmann constant, η is the fluid viscosity, and d is the particle diameter. This equation provides estimation on the effect of Brownian motion on the thermal conductivity by comparing the time scale of particle motion with that of heat diffusion in the liquid. By comparing the time required for a particle to move by the distance equal to its size with time required for heat to move in the liquid by the same distance, Keblinski's team demonstrated that the thermal diffusion is much faster than Brownian diffusion, even when nanoparticles are considered. It was concluded that the movement of nanoparticles due to Brownian motion is too slow to transport significant amounts of heat through a nanofluid. However, Brownian motion could have an important and indirect role in producing particle clustering, which in turn could enhance thermal conductivity.

3.4.2. Liquid layering at liquid/particle interface

Layering of the liquid at the solid interface (interface effect) could enhance thermal conductivity, by which the atomic structure of the liquid layer is significantly more ordered than that of bulk liquid. Because crystalline solids display much better thermal transport than liquids, such layering at the interface would be expected to increase thermal conductivity. To estimate an upper limit for this effect, it was assumed that the thermal conductivity of this interfacial liquid is the same as that of the solid. The resultant larger effective volume of the particle-layered-liquid structure would enhance the thermal conductivity. However, several studies have shown a typical interfacial width that is only on the order of a few atomic distances ($\approx$1 nm). Thus, it was concluded that although the presence of an interfacial layer may play a role in heat transport, it is not likely to be solely responsible for the thermal conductivity enhancement.

3.4.3. Nature of heat transport in nanoparticles

In crystalline solids, such as those used in nanofluids, heat is carried by phonons, i.e., by propagating lattice vibrations. Such phonons are created at random, propagate in random directions, are scattered by each other or by defects, and thus justify the macroscopic theory of heat transport. Analysis done by Keblinski's team identified that phonons cannot diffuse in the $\approx$10 nm particles but must move ballistically across the particle, thus demonstrating that the assumption of diffusive heat transport in nanoparticles is not valid. There are other ballistic phonon effects that could lead to significant increase in thermal conductivity, such as ballistic phonons initiated in one particle can persist in the liquid and reach a nearby particle, a major increase in thermal conductivity is expected. The particles in nanofluids are close together even at relatively low packing factions. Because the particles move constantly due to Brownian motion, locally, they may be much closer and thus enhance coherent phonon heat flow among the particles.

3.4.4. Effects of nanoparticle clustering

Clustering of particles into percolating patterns would have a major effect on the effective thermal conductivity. However, clustering to the extent that solid agglomerates span large distances are unlikely and large clusters would settle down most likely. The effective volume of a cluster, i.e., the volume from which other clusters are excluded, can be much larger than the physical volume of the particles. Since within such clusters, heat can move very rapidly, the volume fraction of highly conductive phase is larger than the volume of solid and according to HC equation may significantly increase thermal conductivity.

3.5. Thermal conductivity

As mentioned earlier, thermal conductivity is one of the most important parameter for enhancing heat transfer performance of a heat transfer fluid and many experimental studies have been done regarding this aspect. Some of the methods used in measuring the thermal conductivity are transient hot wire (THW) method [27], temperature oscillations method, and finally steady-state parallel-plate technique. Transient hot wire method is most utilized as this is the most accurate way to measure the thermal conductivities of materials. This method works by measuring the temperature and time response of the wire to an abrupt electrical pulse. The wire functions as both heater and thermometer. A deviation of Fourier's law and temperature data are used to calculate the thermal conductivity. The wire is coated with a thin layer of electrical insulation to avoid problems with measuring electrically conducting fluids.

Zhang et al. [42] reported accurate measurements of the effective thermal conductivity and thermal diffusivity of various nanofluids by using a transient short-hot-wire (SHW) method. To remove the influences of the static charge and electrical conductance of the nanoparticles on measurements accuracy, the SHW probes are coated by pure Al_2O_3 thin film. To provide excellent electrical insulation and heat conduction, Nagasaka and Nagashima [43] came up with a modified hot-wire cell and electrical system by coating the hot wire with an epoxy adhesive. However, Das et al. [44] raised the concern of possible concentration of ions of the conducting fluids around the hot wire may affect the accuracy of such experiments. Another method in measuring the thermal conductivity is the oscillation method was proposed by Czarnetzki and Roetzel [45]. Since this method was purely thermal and electrical components of the apparatus are removed from the test sample, ion movement should not affect the measurement.

The thermal conductivities of solid nanoparticles are much higher than that of fluids, thus the particles are responsible for the increase in thermal conductivity and heat transfer performance. Many experimental investigations have been conducted and many factors such as size, volume fraction, thermal conductivity of nanoparticles, viscosity, temperature and thermal conductivity of base fluids are reported to influence the thermal conductivity of nanofluids. Generally, most findings report that the thermal conductivity increases with the volume fraction of the nanoparticles. A study done by Choi et al. [38] by using carbon nanotubes in oil as base fluid reported nonlinear increase in thermal conductivity with increased nanotube loading. Their measured thermal conductivity is much higher than theoretical predictions. It was concluded that the nature of heat conduction in nanotube suspensions and an organized structure at the solid-liquid interface is a responsible factor. In another experiment, Eastman et al. [28] measured the thermal conductivity of nanofluids containing Al_2O_3, CuO, and Cu nanoparticles with two different base fluids: water and HE-200 oil. They observed a 60% improvement of the thermal conductivity compared to the corresponding base fluids for only 5% volume of nano particles. One of the highest thermal conductivity improvements in a liquid was observed by Choi et al. [38], where they dispersed multi walled nanotubes (MWNT) into a host material, synthetic poly(α-olefin) oil. They discovered that nanotubes yield an anomalously high increase in thermal conductivity of almost 150% at approximately 1% volume of nanotubes.

Kakaç and Pramuanjaroenkij [46] reported in their review that further research is necessary to develop a good theory to predict thermal conductivity of nanofluids. The thermal conductivity enhancement ratio is given by the ratio of thermal conductivity of the nanofluid to the thermal conductivity of the base fluid (K_{eff}/K_1). Some of the existing empirical correlations to calculate effective thermal conductivity are based on classical research of Maxwell where the effective thermal conductivity is given by:

$$K_{\mathrm{eff,Maxwell}} = \frac{2K_2 + K_1 + \phi(K_2 - K_1)}{2K_2 + K_1 - 2\phi(K_2 - K_1)} \quad (4)$$

where K_1 and K_2 are the thermal conductivity of the fluid and the particle respectively and ϕ is the particle volume fraction. Maxwell's work is based on the assumption that the discontinuous phase is spherical in shape and the thermal conductivity of nanofluids depends on the thermal conductivity of spherical particles, the base fluid and the particle volume fraction. This work was continued by Hamilton and Crosser (HC) to cover none spherical particles and introduce the shape factor (n) which can be determined experimentally for different materials. Their goal was to develop a model as a function of particle shape, composition and the conductivity of both continuous and discontinuous phases. HC model for a discontinuous phase (particles) dispersed in a continuous phase is:

$$K_{\mathrm{eff,HC}} = K_1 \left[\frac{K_2 + (n-1)K_1 - (n-1)\phi(K_1 - K_2)}{K_2 + (n-1)K_1 + \phi(K_1 - K_2)} \right] \quad (5)$$

where the empirical shape factor (n) is defined by $n = 3/\Psi$ and Ψ is the sphericity defined as the ratio of the surface areas of a sphere with the volume equal to that of the particle. The model is valid as long as the thermal conductivity of the particles is larger than thermal conductivity of the continuous phase by at least a factor of 100.

3.6. Viscosity

Wang and Mujumdar [47] reported that there were limited studies on rheological behavior of nanofluids. The viscosity of water with CuO nanoparticle suspensions was measured by Li et al. [48] using a capillary viscometer. Their study has concluded that the apparent viscosity of nanofluids is decreased with increasing temperature. They also pointed out that the capillary tube diameter may influence the apparent viscosity for higher nanoparticle mass fractions, especially at lower temperatures. Another study done by Das et al. [49] measured the viscosity of Al_2O_3–water nanofluids against shear rate. They reported an increase in viscosity with increased particle concentrations and stated that there was a strong possibility that nanofluid may be a non-Newtonian fluid, even viscoelastic in some cases. They suggested further experimental studies to define the viscosity models of nanofluids to obtain more accurate simulation studies. Ding et al. [50] measured the viscosity of CNT-water nanofluids as a function of shear rate. Their observation showed that the viscosity of nanofluids increased with increasing CNT concentration and decreasing temperature. They also observed shear thinning behavior, which means that nanofluids can provide better fluid flow performance due to higher shear rate at the wall, which results in low viscosity.

3.7. Convection

Convective heat transfer of nanofluids is another area in nanofluids that receive little attention since only few studies have been focused on convective heat transfer of nanofluids compared

Table 3
The main findings from the experimental and numerical work related to nanofluids.

Author	Type[a]	Method	Findings
Trisaksri and Wongwises [52]	E	Study on silicon microchannel heat sink with NF as coolant	Performance of heat sink greatly improved NF did not produce extra pressure drop
Chein and Huang [53]	E	Microchannel heat sink with nanofluid	At low flow rate, NF could absorb more heat, Raising the NF bulk temperature could prevent the particles from agglomerating, Slight increase in pressure drop due to NF
Pantzali et al. [55]	N + E	Effects of NF on miniature plate HE with modulated surface	Nanoparticles increase thermal conductivity Heat transfer enhancement is more at lower flow rate
Jang and Choi [56]	N	Performance of microchannel heat sink with NF	10% increase with the use of NF compared to water

[a] E—experimental analysis and N—numerical analysis.

to thermal conductivity. Forced convective flow is dependent on both Reynolds and Prandtl numbers, but for nanofluids the thermal properties of all the constituents need to be taken into account. Kim et al. [51] performed an experimental study to investigate convective heat transfer characteristics of nanofluids under laminar and turbulent flow conditions. Their study yielded the following results: for alumina nanofluids at 3% volume, the enhancement of convective heat transfer coefficient is increased to 15% and 20%. For the amorphous carbonic nanofluids at 3.5% volume, the enhancement of convective heat transfer coefficient is increased only 8% in laminar flow, while no convection increment was shown in turbulent flow. They concluded that the thermal conductivity enhancement had a key role in the convection of nanofluids. Trisaksri and Wongwises [52] pointed out that the conclusions from experimental and analytical investigations are in disagreement. Analytical investigations suggest that natural convective heat transfer of nanofluids increases as particle volume fraction and density increase, but experimental results are opposite.

3.8. Experimental studies on nanofluids

Most experimental studies done on nanofluids focus on the thermal conductivity and are measured using the methods mentioned before and reported enhanced thermal conductivity with the addition of nanoparticles. Chein and Huang [53] carried out a study on silicon microchannel heat sink performance using nanofluids as coolant. Their study reported that the performance of the heat sink was greatly improved due to the fact that nanofluids contain higher thermal conductivity and thermal dispersion effects. They also observed that the nanofluids did not produce extra pressure drop because of small particle size and low particle volume fraction.

In a different study by Chein and Chuang [54], a CuO–H_2O mixture was used without dispersion agent as coolants to study the performance of a microchannel heat sink (MCHS). Their study showed that nanofluids could absorb more heat than water cooled MCHS when the flow rate was low, while for high flow rate the heat transfer was dominated by the volume flow rate and nanoparticles did not contribute. It was found that raising nanofluid bulk temperature could prevent the particles from being agglomerated into larger scale particle clusters. In terms of pressure drop, only slight increase was observed due to the presence of nanoparticles.

Pantzali et al. [55] studied numerically and experimentally the effects of nanofluids on the performance of a miniature plate heat exchanger with modulated surface. Their thermophysical measurements of the nanofluid (CuO in water, 4% volume) reveal that the increase in thermal conductivity is accompanied by a significant drop in heat capacity and an increase in viscosity. Besides that, it was outlined that the heat transfer enhancement is more at lower flow rate and at higher flow rate, where the main heat transport mechanism is convection, nanoparticle contribution is limited. For a given heat duty, the amount of nanofluid volumetric flow rate required is lower than of water, resulting in lower pressure drop and less pumping power.

3.9. Numerical studies on nanofluids

Jang and Choi [56] analyzed the cooling performance of a microchannel heat sink with nanofluids. Their theoretical model was based on the analysis done by Jang and Choi [57], where thermal conductivity of nanofluids involves four modes of energy transport, as follows: thermal diffusion of base fluid; thermal diffusion in nanoparticles; collision between nanoparticles; and nanoconvection due to Brownian motion. Their results showed that the cooling performance of the microchannel heat sink with water-based nanofluids containing diamond (1% vol, 2 nm) is enhanced by about 10% compared with that of a microchannel heat sink with water.

According to a review done by Wang and Mujumdar [58], two approaches have been adopted in most numerical studies to investigate the heat transfer characteristics of nanofluids. The first approach assumes that the continuum theory is still valid for fluids with suspended nanoparticles. The second approach uses a two-phase model for a better description of both the fluid and the solid phases, but this method is not common. This is because the single phase model is simpler and computationally more efficient. Another approach is to adopt the Boltzmann theory which states the heat transfer enhancement using nanofluids may be affected by several factors such as the Brownian motion, layering at the solid/liquid interface, ballistic phonon transport through the particles, nanoparticle clustering and the friction between the fluid and the solid particles. However, this method is complicated as it is difficult to describe all those phenomena mathematically. Some of the major findings related to nanofluids research reviewed previously are summarized in Table 3.

4. Conclusions

This review covered some basic concepts and literatures related to microchannel heat exchanger and nanofluids. Generally, the contents were categorized according to microchannel heat exchanger and nanofluids. This included literatures relating to MCHE, which included types of MCHE, manufacturing methods, microfluidics

concepts and findings, and finally experimental and numerical literature reviews on nanofluids. Most experimental and numerical studies reported that enhanced heat transfer with the use of microchannels but it came at the cost of increased pressure drop. It can be safely said that the amount of understanding and knowledge is still at the early stage and much research is necessary to fully establish the concepts of micro channels and microfluidics. Literatures on nanofluids included preparation of these fluids, discussion on the heat transfer properties and characteristic and some numerical and experimental results. The mechanisms involved in the heat transport phenomena are still not fully understood yet, but the increased heat transfer abilities continues to impress researchers. Much further analysis is needed to establish the concepts in this field as it is still considered as a novel idea and implementation of nanofluids in industries is still far from being a practical solution at this moment. This review also identified a problem related to research in these fields, which is the lack of standardization among different studies. This could be one of the main reasons for the deviations obtained in the results of most of the studies. However, as a general conclusion, it is evident in most cases that microchannel heat exchanger and nanofluids seems like the only plausible solution at this moment for the cooling challenge in the micro and nanotechnology era. As a recommendation, it would be beneficial to have a widespread communication and network among researchers in this field to have a more systematic approach towards the research and accelerated development of these technologies.

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